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Wang et al.

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(54) **METHOD AND APPARATUS OF BEAM TRAINING FOR MIMO OPERATION**

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(51) **Int. Cl.**

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H04B 7/04	(2006.01)
H04B 7/06	(2006.01)
H04B 7/08	(2006.01)

(52) **U.S. Cl.**

CPC ***H04B 7/043*** (2013.01); *H04B 7/0417* (2013.01); ***H04B 7/0695*** (2013.01); ***H04B 7/088*** (2013.01)

(58) **Field of Classification Search**

CPC .. H04B 7/0617; H04B 7/0628; H04B 7/0417; H04B 7/0491; H04B 7/0634

USPC 375/229–236, 259–285, 295–352

See application file for complete search history.

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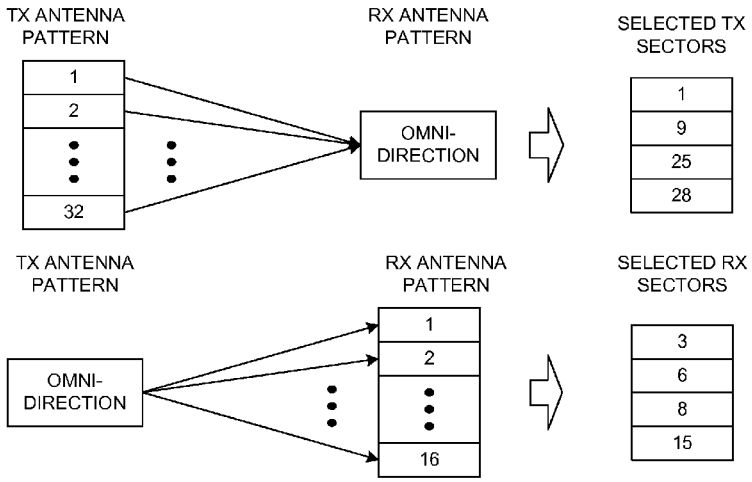
(57) **ABSTRACT**

The disclosed invention provides an efficient method for beam training to enable spatial multiplexing MIMO operation and spatial combining in a wireless network. The invention discloses a simple and efficient beam-training algorithm and protocol for MIMO operation that operates in high SNR condition for reliable MIMO operation. In one novel aspect, the best MIMO beam combinations are determined after TX sector sweeping and RX sector sweeping. In addition, the selection criteria includes not only signal quality, but also considers mutual interference and leakage among multiple MIMO spatial streams to improve overall MIMO performance.

16 Claims, 7 Drawing Sheets



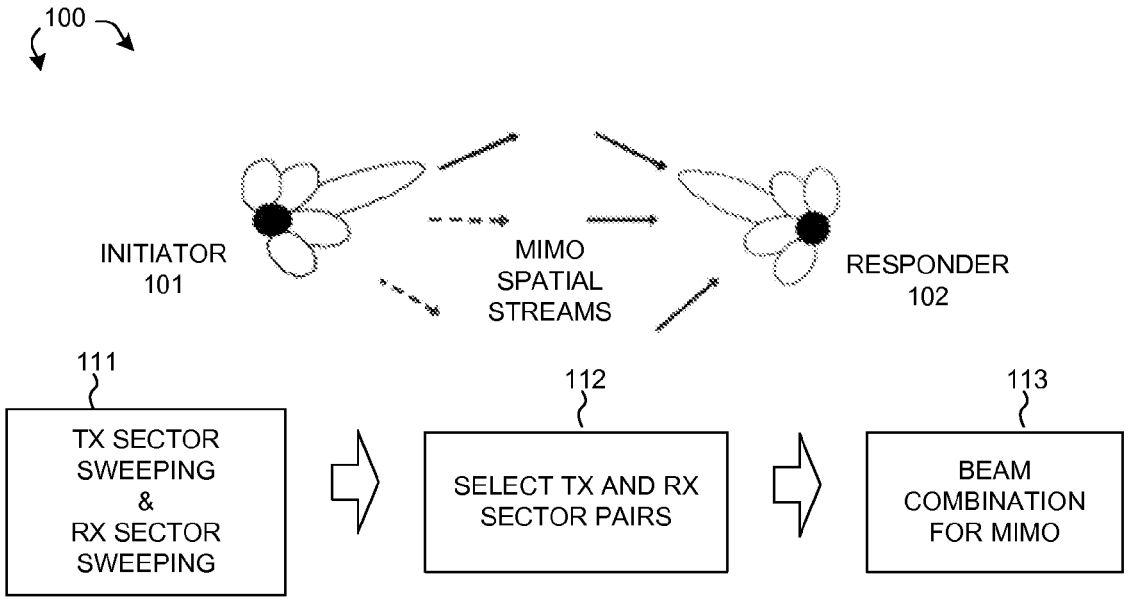

100
INITIATOR
101
MIMO
SPATIAL
STREAMS
RESPONDER
102
111
TX SECTOR
SWEEPING
&
RX SECTOR
SWEEPING
112
SELECT TX AND RX
SECTOR PAIRS
113
BEAM
COMBINATION
FOR MIMO

FIG. 1

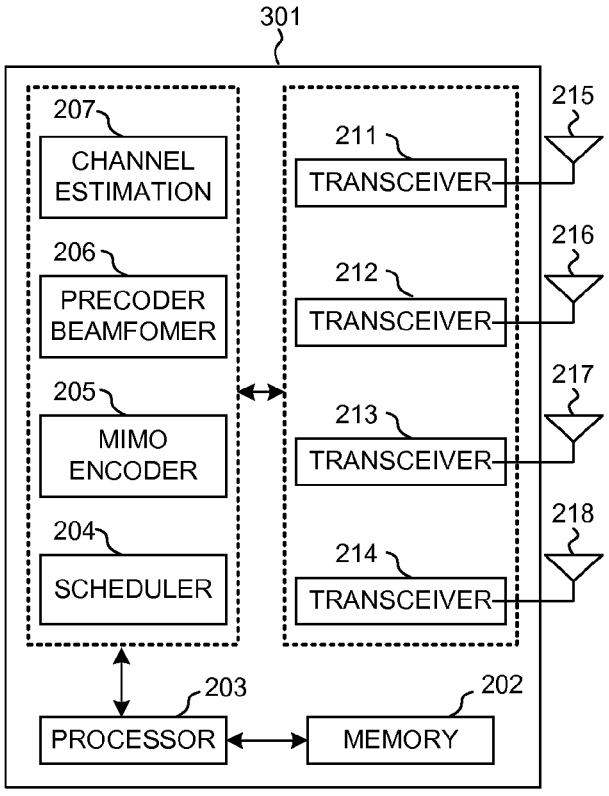

301
207
CHANNEL
ESTIMATION
206
PRECODER
BEAMFOMER
205
MIMO
ENCODER
204
SCHEDULER
211
TRANSCEIVER
212
TRANSCEIVER
213
TRANSCEIVER
214
TRANSCEIVER
215
216
217
218
203
PROCESSOR
202
MEMORY

FIG. 2

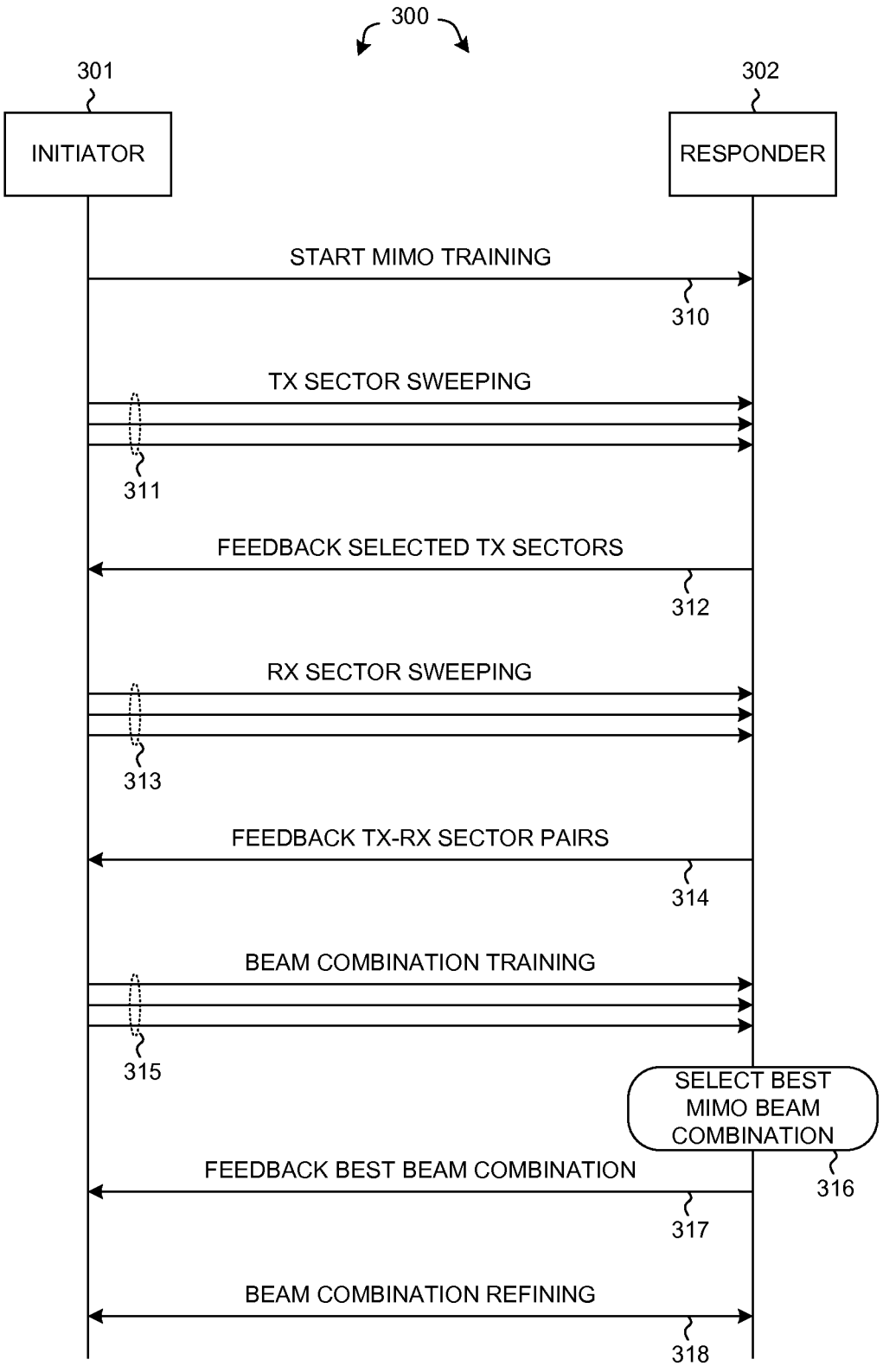

300
301
INITIATOR
302
RESPONDER
START MIMO TRAINING
310
TX SECTOR SWEEPING
311
FEEDBACK SELECTED TX SECTORS
312
RX SECTOR SWEEPING
313
FEEDBACK TX-RX SECTOR PAIRS
314
BEAM COMBINATION TRAINING
315
SELECT BEST MIMO BEAM COMBINATION
316
FEEDBACK BEST BEAM COMBINATION
317
BEAM COMBINATION REFINING
318

FIG. 3

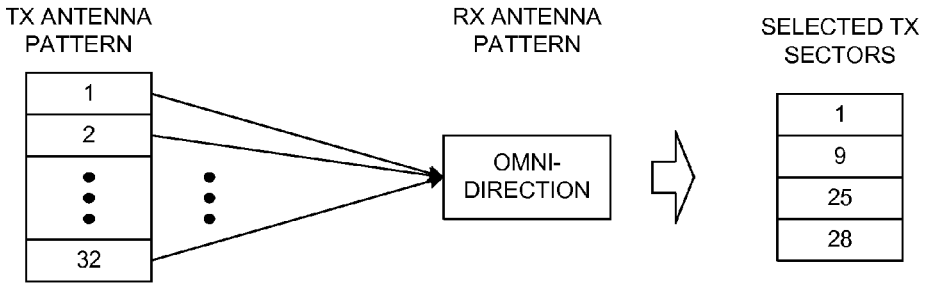


FIG. 4A

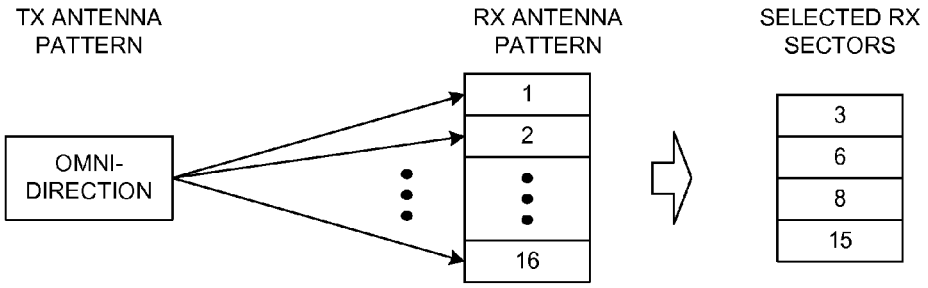


FIG. 4B

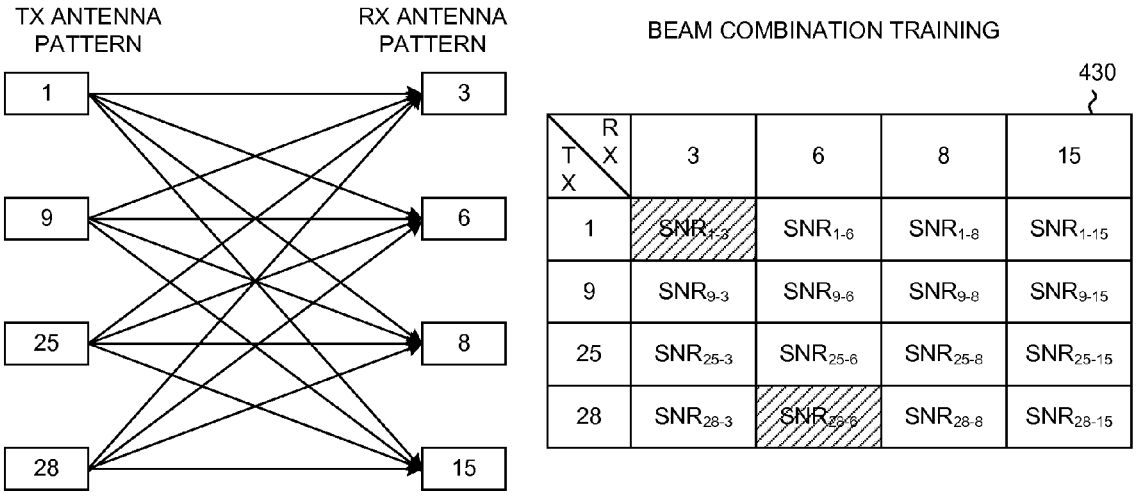


FIG. 4C

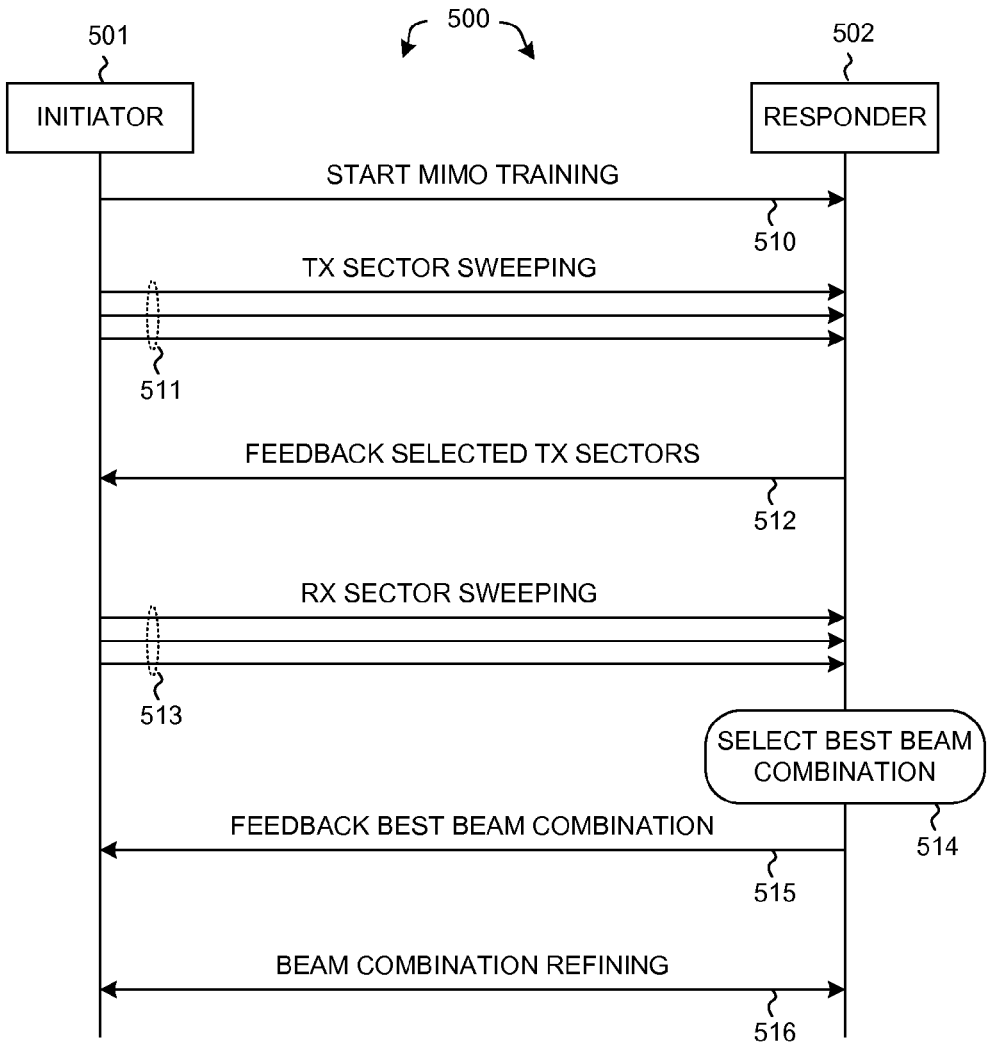

500
501
INITIATOR
502
RESPONDER
START MIMO TRAINING
510
TX SECTOR SWEEPING
511
FEEDBACK SELECTED TX SECTORS
512
RX SECTOR SWEEPING
513
SELECT BEST BEAM COMBINATION
514
FEEDBACK BEST BEAM COMBINATION
515
BEAM COMBINATION REFINING
516

FIG. 5

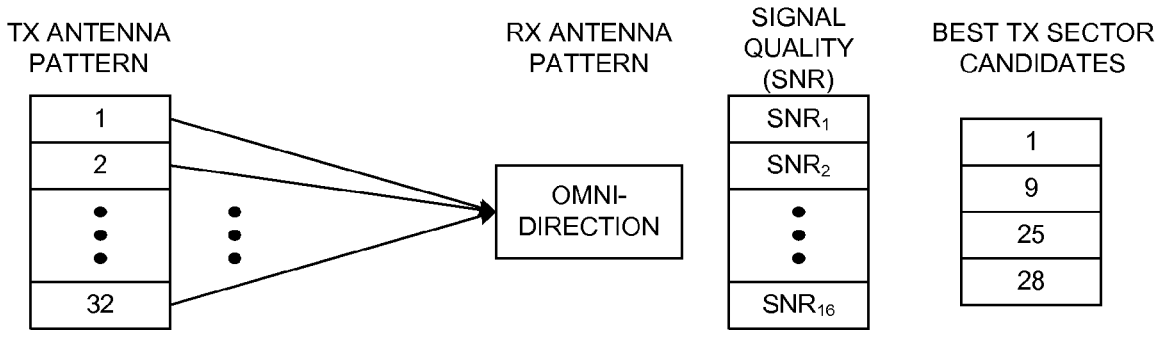

TX ANTENNA PATTERN
1
2
32
RX ANTENNA PATTERN
OMNI-DIRECTION
SIGNAL QUALITY (SNR)
SNR1
SNR2
SNR16
BEST TX SECTOR CANDIDATES
1
9
25
28

FIG. 6A

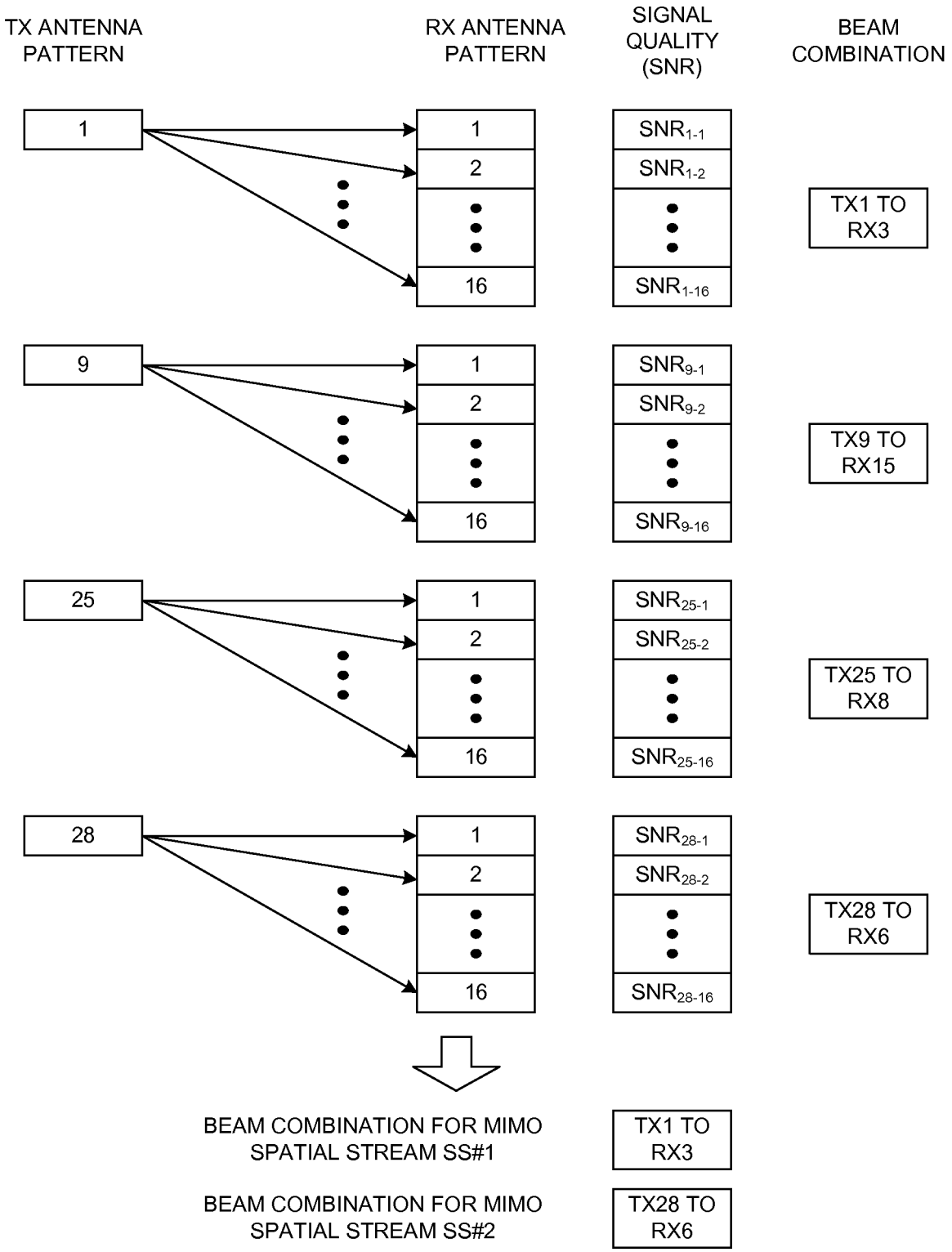

TX ANTENNA PATTERN
RX ANTENNA PATTERN
SIGNAL QUALITY (SNR)
BEAM COMBINATION
1
1
2
16
SNR1-1
SNR1-2
SNR1-16
TX1 TO RX3
9
1
2
16
SNR9-1
SNR9-2
SNR9-16
TX9 TO RX15
25
1
2
16
SNR25-1
SNR25-2
SNR25-16
TX25 TO RX8
28
1
2
16
SNR28-1
SNR28-2
SNR28-16
TX28 TO RX6
BEAM COMBINATION FOR MIMO SPATIAL STREAM SS#1
TX1 TO RX3
BEAM COMBINATION FOR MIMO SPATIAL STREAM SS#2
TX28 TO RX6

FIG. 6B

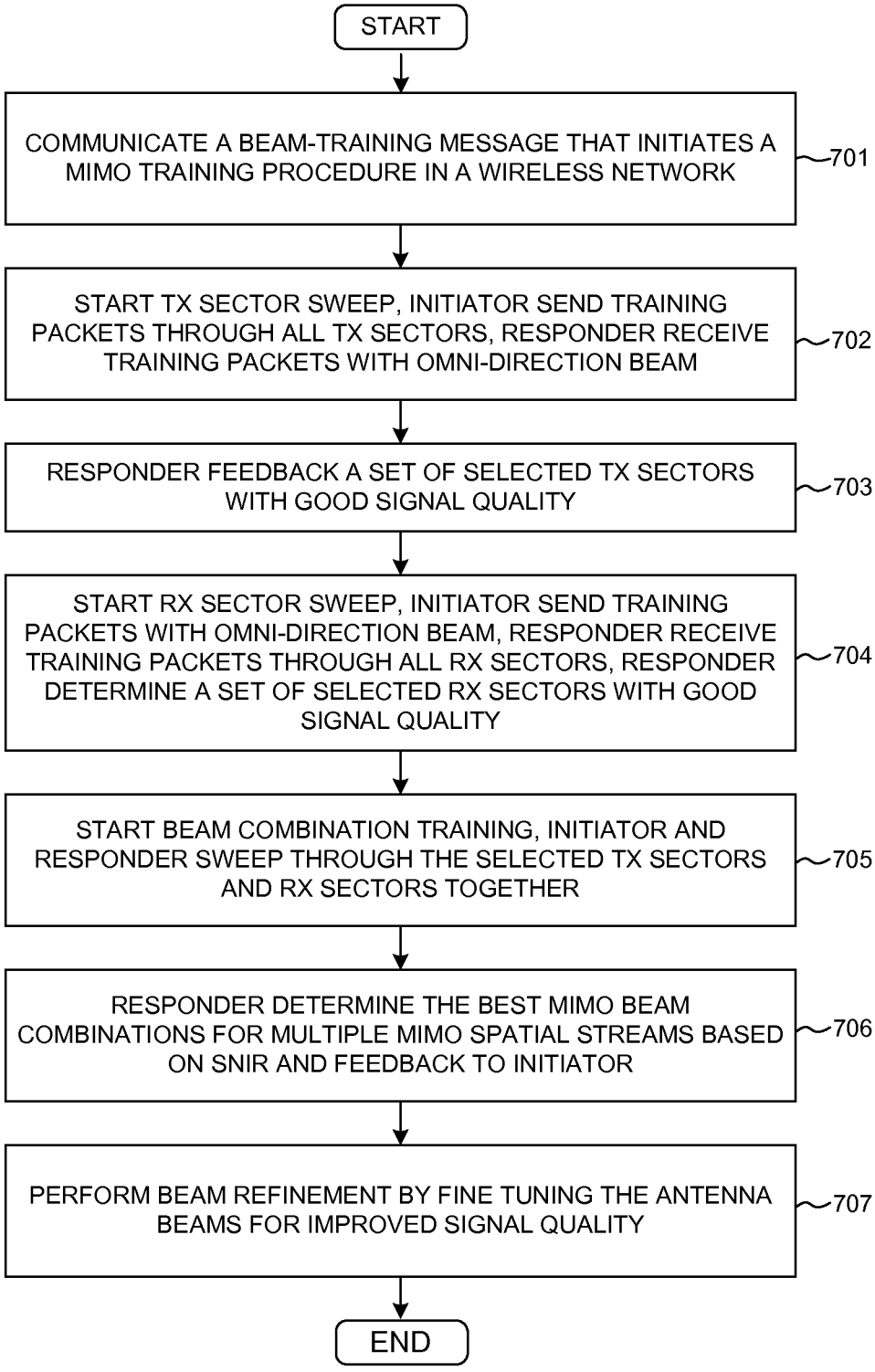

START
COMMUNICATE A BEAM-TRAINING MESSAGE THAT INITIATES A MIMO TRAINING PROCEDURE IN A WIRELESS NETWORK
701
START TX SECTOR SWEEP, INITIATOR SEND TRAINING PACKETS THROUGH ALL TX SECTORS, RESPONDER RECEIVE TRAINING PACKETS WITH OMNI-DIRECTION BEAM
702
RESPONDER FEEDBACK A SET OF SELECTED TX SECTORS WITH GOOD SIGNAL QUALITY
703
START RX SECTOR SWEEP, INITIATOR SEND TRAINING PACKETS WITH OMNI-DIRECTION BEAM, RESPONDER RECEIVE TRAINING PACKETS THROUGH ALL RX SECTORS, RESPONDER DETERMINE A SET OF SELECTED RX SECTORS WITH GOOD SIGNAL QUALITY
704
START BEAM COMBINATION TRAINING, INITIATOR AND RESPONDER SWEEP THROUGH THE SELECTED TX SECTORS AND RX SECTORS TOGETHER
705
RESPONDER DETERMINE THE BEST MIMO BEAM COMBINATIONS FOR MULTIPLE MIMO SPATIAL STREAMS BASED ON SNIR AND FEEDBACK TO INITIATOR
706
PERFORM BEAM REFINEMENT BY FINE TUNING THE ANTENNA BEAMS FOR IMPROVED SIGNAL QUALITY
707
END

FIG. 7

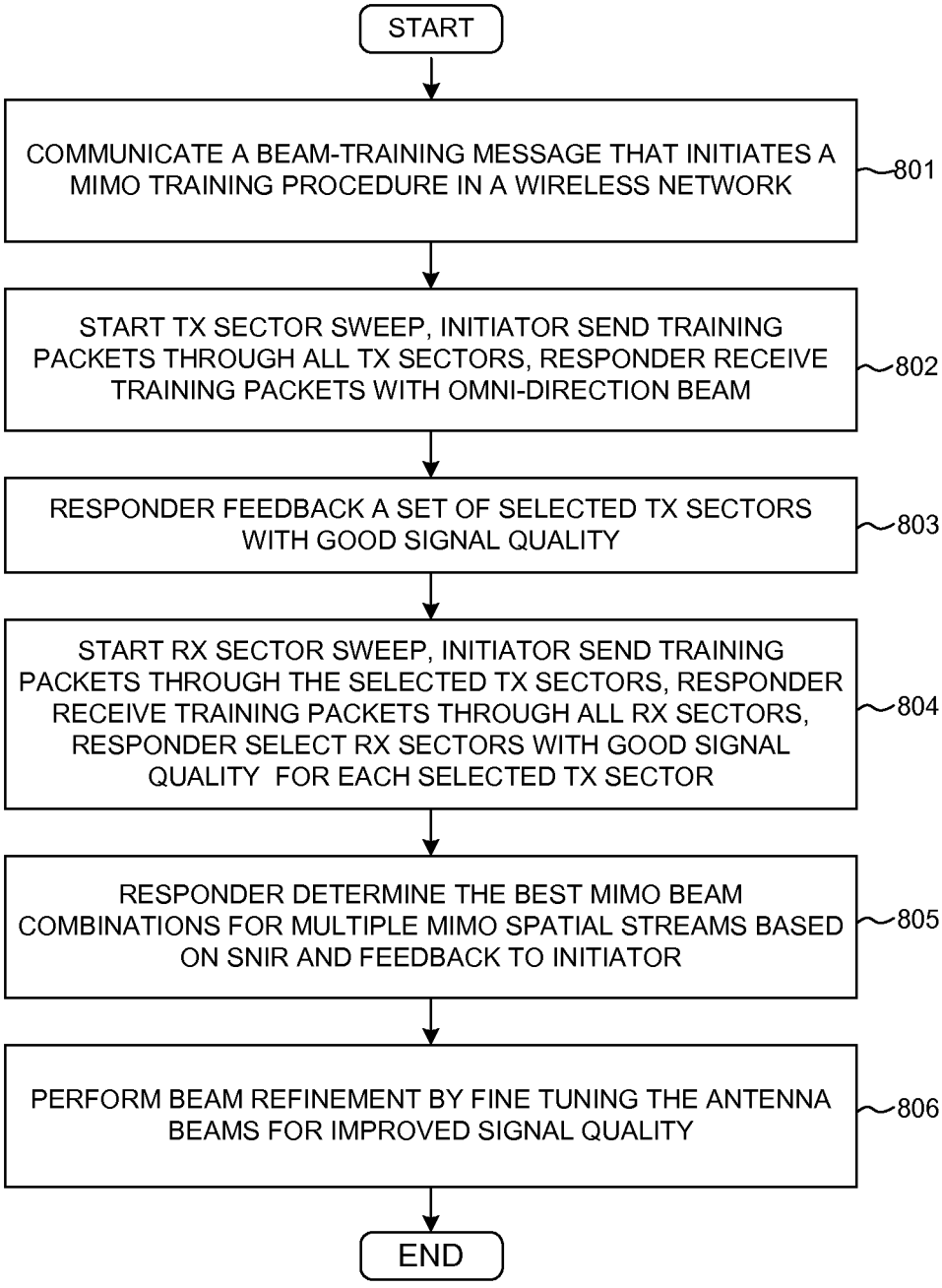

START
COMMUNICATE A BEAM-TRAINING MESSAGE THAT INITIATES A MIMO TRAINING PROCEDURE IN A WIRELESS NETWORK
801
START TX SECTOR SWEEP, INITIATOR SEND TRAINING PACKETS THROUGH ALL TX SECTORS, RESPONDER RECEIVE TRAINING PACKETS WITH OMNI-DIRECTION BEAM
802
RESPONDER FEEDBACK A SET OF SELECTED TX SECTORS WITH GOOD SIGNAL QUALITY
803
START RX SECTOR SWEEP, INITIATOR SEND TRAINING PACKETS THROUGH THE SELECTED TX SECTORS, RESPONDER RECEIVE TRAINING PACKETS THROUGH ALL RX SECTORS, RESPONDER SELECT RX SECTORS WITH GOOD SIGNAL QUALITY FOR EACH SELECTED TX SECTOR
804
RESPONDER DETERMINE THE BEST MIMO BEAM COMBINATIONS FOR MULTIPLE MIMO SPATIAL STREAMS BASED ON SNIR AND FEEDBACK TO INITIATOR
805
PERFORM BEAM REFINEMENT BY FINE TUNING THE ANTENNA BEAMS FOR IMPROVED SIGNAL QUALITY
806
END

FIG. 8

METHOD AND APPARATUS OF BEAM TRAINING FOR MIMO OPERATION

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority under 35 U.S.C. §119 from U.S. Provisional Application No. 61/650,220, entitled "Method and Apparatus for Beam Training for MIMO Operation," filed on May 22, 2012, the subject matter of which is incorporated herein by reference.

TECHNICAL FIELD

The disclosed embodiments relate generally to wireless network communications, and, more particularly, to beam training methods for multiple-input multiple-output (MIMO) operation.

BACKGROUND

Spatial multiplexing multiple input and multiple output (MIMO) technique is used to increase the data rate (and spectral efficiency) by transmitting multiple data streams via different spatial paths simultaneously. Spatial combining technique, on the other hand, refers to the technique that combines the same data stream via different spatial paths to enhance signal quality. Spatial multiplexing and spatial combining techniques have been widely employed in mobile communications systems such as IEEE 802.11n (2.4 GHz and 5 GHz) and IEEE 802.11ac (5 GHz). For 802.11n and 802.11ac, the signal wavelength is large comparing to the feature size of objects in the propagation environment. As a result, NLOS signal propagation is dominated by the signal scattering from various objects. Due to the severe scattering, OFDM signal is often used in such systems and the spatial multiplexing and spatial combining are done on a per-tone (per-subcarrier) basis in the digital domain.

For higher frequency systems such as IEEE 802.11ad (60 GHz), the signal propagation characteristics change as the signal wavelength becomes small comparing to the feature size of objects in the propagation environment. As a result, signal propagation is dominated by ray-like propagation with discrete paths in space. The signal quality can be greatly enhanced if either TX or RX antenna beams or both TX and RX antenna beams are directed toward strong spatial signal path. The improved signal quality via aligning the antenna beams with strong spatial signal path manifests both increased signal strength (higher signal-to-noise ratio) and reduced delay spread. Since the delay spread is reduced, spatial combining can be wholly or partially done in RF domain (instead of digital domain) to simplify implementation.

In general, phased-array antenna with steerable antenna beam in MIMO operation provides antenna gain and enables mobility. Eigen-beamforming is one method of antenna beam training. The Eigen-beamforming requires transmitter and receiver to estimate the channel response matrix first. The channel response matrix is then decomposed using singular value decomposition (SVD). The MIMO operation uses n dominant Eigen modes (corresponding to n spatial paths) for transmitting n spatial streams. The Eigen beamforming method suffers from the problem that the channel response matrix is obtained in lower signal-to-noise condition since no beamforming is used during the channel estimation.

Another method of antenna beam training is multi-stage iterative training using power method. In the power method, the receiver sends back the normalized receive vector in the n antennas to the transmitter. The transmitter uses the receive vector as the next transmit antenna weight. The antenna weight quickly converges to the first Eigen vector after a few iterations. This process continues until the n vectors (antenna weight vectors) are obtained. The power method suffers from the problem that it only works (converges) in the presence of high signal-to-noise ratio.

The beam training protocol provided in IEEE 802.11ad involves either transmitter or receiver to sweep through a number of antenna beam directions to determine the beam with the best signal quality. For efficient beam training, multiple stages of beam training are provided. The initial stage, called the SLS (sector level sweep), provides coarse antenna beam training. The subsequent stage, called the beam refinement protocol or beam tracking, provides the fine-tuning of antenna beam for improved pointing accuracy and higher signal quality. These beam training protocols are generally used to train a single spatial beam for the transmission of a single data stream.

A solution is sought for training multiple antenna beam combinations to allow for multiple data streams for increased data rate, or to allow combining of the same data stream for enhanced signal quality.

SUMMARY

The disclosed invention provides an efficient method for beam training to enable spatial multiplexing MIMO operation and spatial combining in a wireless network. The invention discloses a simple and efficient beam-training algorithm and protocol for MIMO operation that operates in high SNR condition for reliable MIMO operation without the drawbacks of prior art methods.

In a first embodiment, an initiator and a responder exchange beam-training parameters to start a MIMO training procedure. During TX sector sweeping, the initiator sends training packets through all TX sectors, while the responder receives the training packets with omni-direction beam. The responder sends back a set of selected TX sectors with good received signal quality. During RX sector sweeping, the initiator sends training packet with omni-direction beam, while the responder receives the training packets through all RX sectors. The responder determines a set of selected RX sectors with good received signal quality. During beam combination training, the initiator and the responder sweep through the selected TX sectors and RX sectors together. The responder determines the best MIMO beam combinations for multiple MIMO spatial streams based on SNIR and sends back to the initiator. Finally, beam refinement is performed to fine-tune the antenna beams for improved signal quality. In one novel aspect, the leakage from one spatial stream into the receive beam of another spatial stream is considered as interference for SNIR calculation.

In a second embodiment, an initiator and a responder exchange beam-training parameters to start a MIMO training procedure. During TX sector sweeping, the initiator sends training packets through all TX sectors, while the responder receives the training packets with omni-direction beam. The responder sends back a set of selected TX sectors with good received signal quality. During RX sector sweeping, the initiator sends training packet using each selected TX sector, while the responder receives the training packets through all RX sectors. The responder selects one RX sector with good received signal quality for each selected TX sector. The responder determines the best MIMO beam combinations for multiple MIMO spatial streams based on SNIR and sends

back to the initiator. Finally, beam refinement is performed to fine-tune the antenna beams for improved signal quality. In one novel aspect, the leakage from one spatial stream into the receive beam of another spatial stream is considered as interference for SNIR calculation.

Other embodiments and advantages are described in the detailed description below. This summary does not purport to define the invention. The invention is defined by the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a MU-MIMO operation with antenna beam training for multiple spatial streams in a wireless system in accordance with one novel aspect.

FIG. **2** illustrates a simplified block diagram of a wireless device in a wireless system in accordance with one novel aspect.

FIG. **3** illustrates a message/signal exchange flow of a first embodiment of antenna beam training for MIMO operation.

FIG. **4**A illustrates a first step of the first embodiment of antenna beam training.

FIG. **4**B illustrates a second step of the first embodiment of antenna beam training.

FIG. **4**C illustrates a third step of the first embodiment of antenna beam training.

FIG. **5** illustrates a message/signal exchange flow of a second embodiment of antenna beam training for MIMO operation.

FIG. **6**A illustrates a first step of the second embodiment of antenna beam training.

FIG. **6**B illustrates a second step and a third step of the second embodiment of antenna beam training.

FIG. **7** is a flow chart of a first embodiment of a method of antenna beam training for MIMO operation in accordance with a novel aspect.

FIG. **8** is a flow chart of a second embodiment of a method of antenna beam training for MIMO operation in accordance with a novel aspect.

DETAILED DESCRIPTION

Reference will now be made in detail to some embodiments of the invention, examples of which are illustrated in the accompanying drawings.

FIG. **1** illustrates a MU-MIMO operation with antenna beam training for multiple spatial streams in a wireless system **100** in accordance with one novel aspect. Wireless system **100** comprises an initiator **101** and a responder **102**. Both initiator **101** and responder **102** are equipped with antenna arrays to support MIMO operation for multiple spatial streams. To enable MIMO operation, initiator **101** signals to responder **102** to start a MIMO training with a list of MIMO training parameters. The purpose of MIMO training is for antenna array beamforming, where both transmitting antennas and receiving antennas are steered with the best beam combinations to increase data rate and enhance signal quality.

In the example of FIG. **1**, the intended direction is initiator **101** is the transmitter of MIMO signal and responder **102** is the receiver of MIMO signal. Note that an initiator can also initiate a MIMO training in which the initiator is the receiver of MIMO signal. In step **111**, initiator **101** performs TX sector sweeping, where training packets are transmitted to responder **102** through the TX sectors, each sector corresponds to a specific TX antenna beam/pattern (e.g., direction/weight). During RX sector sweeping, training packets are transmitted from initiator **101** to responder **102**, which sweeps through the RX sectors, each sector corresponds to a specific RX antenna beam/pattern (e.g., direction/weight). In step **112**, responder **102** records the received signal quality (e.g., signal-to-noise ratio (SNR)) and determines a number of beam combinations (selected TX and RX sector pairs) based on the results of TX sector sweep and RX sector sweep. The number of beam combinations needs to be greater or equal to the number of spatial streams. In step **113**, from the selected TX and RX sector pairs, responder **102** determines the best MIMO beam combinations for the multiple MIMO spatial streams based on signal-to-(noise+interference) ratio (SNIR) criteria.

In one novel aspect, the simple and efficient beam training method operates in high SNR condition for reliable operation. Furthermore, by considering mutual interference or leakage among the multiple MIMO spatial streams, the MIMO beam combination selection is more accurate to improve overall MIMO performance.

FIG. **2** illustrates a simplified block diagram of a wireless device **201** in a wireless system in accordance with one novel aspect. Wireless device **201** comprises memory **202**, a processor **203**, a scheduler **204**, a MIMO encoder **205**, a beamformer/precoder **206**, a channel estimation module **207**, and a plurality of transceivers **211-214** coupled to a plurality of antennas **215-218**, respectively. The wireless device receives RF signals from the antenna, converts them to baseband signals and sends them to the processor. RF transceiver also converts received baseband signals from the processor, converts them to RF signals, and sends out to the antenna. Processor **203** processes the received baseband signals and invokes different functional modules to perform features in the device. Memory **202** stores program instructions and data to control the operations of the device. FIG. **2** further illustrates functional modules in the wireless device that carry out embodiments of the current invention. The functional modules may be implemented by hardware, firmware, software, or any combination thereof.

FIG. **3** illustrates a message/signal exchange flow of a first embodiment of antenna beam training for MIMO operation in a wireless communications system **300**. Wireless communications system **300** comprises an initiator **301** and a responder **302**. In step **310**, the initiator sends a MIMO beam-training message to the responder to start a MIMO training procedure. The beam-training message comprises MIMO training parameters such as the number of TX sectors, the number of RX sectors, the number of MIMO spatial streams, the number of candidate beam combinations, and other relevant parameters. For example, the duration and timing of training packets may be included as part of the parameters. In the example of FIG. **3**, the initiator is the transmitter of MIMO signal. However, an initiator can also initiate a MIMO training in which it is the receiver of MIMO signal.

In step **311**, during TX sector sweeping, initiator **301** starts sending training packets to responder **302**. Each training packet is a short packet designed for beam training—allowing the receiver to measure the received signal quality, but not carrying extra data payload to reduce time. For TX sector sweeping, the training packets are sent through all the TX sectors—one packet per sector with a gap (inter-frame spacing) between consecutive training packets. Responder **302** receives the training packets with an omni-direction antenna pattern and records the received signal quality for each TX sector. In step **312**, responder **302** feedbacks a set of selected TX sectors with good received signal quality to initiator **301**. In step **313**, RX sector sweeping is performed. Initiator **301** transmits training packets with a semi-omni antenna pattern while responder **302** sweep through all the RX sectors with dwell time of each RX sector corresponding to the training

packet duration and timing. Responder **302** again records the received signal quality for each RX sector. In step **314**, responder **302** optionally feedbacks the candidate beam combinations (e.g., a list of TX-RX sector pairs) to initiator **301**. Based on the results of TX sector sweep and RX sector sweep, the selection of RX sectors is based on signal quality (e.g., SNR).

In step **315**, the initiator and the responder start sweeping the selected TX sectors and the selected RX sectors together for beam combination training. During the beam combination training, the initiator transmits a training packet through one of the selected TX sectors while the responder receives the training packet through the paired RX sector in one beam combination. Because the initiator already knows the selected TX-RX sector pairs, it knows how many times to send the training packets for each selected TX sector. In an alternative embodiment, the responder might not feedback the beam combinations in step **314**. As long as the initiator knows the number of candidate beam combinations, it still knows how many times to send the training packets for each selected TX sector for beam combination training. The responder records the signal quality for each selected TX-RX sector pair during the beam combination training.

In step **316**, responder **302** determines the best MIMO beam combinations for the multiple MIMO spatial streams. If there are two MIMO spatial streams, then two best MIMO beam combinations are determined. For spatial multiplexing, the best MIMO beam combinations are determined based on the highest SNIR. For spatial combining, the best MIMO beam combinations are determined based on the highest total combined power (SUM power). In step **317**, responder **302** feedbacks the best MIMO beam combinations to initiator **301**. Finally, in step **318**, initiator **301** and responder **302** perform beam refinement, which fine-tunes the antenna beams for improved pointing accuracy and higher signal quality. More details of the first MIMO training embodiment are now described below accompanied with FIGS. **4**A-**4**C.

FIG. **4**A illustrates a first step of the first embodiment of antenna beam training. The first step involves TX sector sweeping after initializing a MIMO training between an initiator and a responder. In the example of FIG. **4**A, the initiator transmits training packets through total thirty-two (32) TX sectors—sectors **1** to **32**. The responder receives the training packets with an omni-direction beam. The responder then selects four TX sectors with the best signal quality (e.g., TX sectors **1**, **9**, **25**, and **28**). The responder also sends the selected TX sectors back to the initiator.

FIG. **4**B illustrates a second step of the first embodiment of antenna beam training. The second step involves RX sector sweeping. In the example of FIG. **4**B, the initiator transmits training packets using an omni-direction beam to the responder, while the responder receives the training packets sweeping through total sixteen (16) RX sectors—sectors **1** to **16**. The responder then selects four RX sectors with the best signal quality (e.g., RX sectors **3**, **6**, **8**, and **15**).

FIG. **4**C illustrates a third step of the first embodiment of antenna beam training. The third step involves beam combination training using the selected TX sectors and the selected RX sectors. In the example of FIG. **4**C, the initiator transmits training packets sweeping through the selected TX sectors (**1**, **9**, **25**, and **28**), while the responder receives the packets sweeping through the selected RX sectors (**3**, **6**, **8**, and **15**). The responder then records the signal quality (SNR) for all sixteen (4 TX sectors×4 RX sectors=16) beam combinations, as depicted by table **430**.

The best MIMO beam combinations for multiple MIMO spatial streams are selected from the sixteen beam combinations. The best beam combination typically means the highest signal quality (SNR). However, in order to select the best beam combinations for multiple spatial streams, the selection criteria needs to include the interference or leakage between the spatial streams. Suppose TX**1**-RX**3** sector pair and TX**28**-RX**6** sector pair are selected as the MIMO beam combinations for two MIMO spatial streams SS**1** and SS**2**, respectively. The received signal power from TX**1** to RX**6** becomes the interference to the TX**28**-RX**6** pair, and the received signal power from TX**28** to RX**3** becomes the interference to the TX**1**-RX**3** pair. After considering the mutual interference or leakage, the responder determines the best two beam combinations for two spatial streams.

FIG. **5** illustrates a message/signal exchange flow of a second embodiment of antenna beam training for MIMO operation in a wireless communications system **500**. Wireless communications system **500** comprises an initiator **501** and a responder **502**. In step **510**, the initiator sends a MIMO beam-training message to the responder to start a MIMO training procedure. The beam-training message comprises MIMO training parameters such as the number of TX sectors, the number of RX sectors, the number of MIMO spatial streams, the number of candidate beam combinations, and other relevant parameters. For example, the duration and timing of training packets may be included as part of the parameters. In the example of FIG. **5**, the initiator is the transmitter of MIMO signal. However, an initiator can also initiate a MIMO training in which it is the receiver of MIMO signal.

In step **511**, during TX sector sweeping, initiator **501** starts sending training packets to responder **502**. Each training packet is a short packet designed for beam training—allowing the receiver to measure the received signal quality, but not carrying extra data payload to reduce time. For TX sector sweeping, the training packets are sent through all the TX sectors—one packet per sector with a gap (inter-frame spacing) between consecutive training packets. Responder **502** receives the training packets with omni-direction antenna pattern and records the received signal quality for each TX sector. In step **512**, responder **502** feedbacks a set of selected TX sectors with good received signal quality to initiator **501**. In step **513**, RX sector sweeping is performed. In the second embodiment, instead of using omni-direction beam for transmitting training packets, initiator **501** transmits through one of the selected TX sectors a number of training packets (corresponding to the number of RX sectors to be swept), while responder **502** sweeps through all the RX sectors. The initiator repeats this process for each selected TX sector while the responder sweeps through all the RX sectors for each selected TX sector. The dwell time of each RX sector corresponds to a training packet duration and timing. Responder **502** again records the received signal quality and selects one RX sector with good signal quality for each selected TX sector.

In step **514**, responder **502** determines the best MIMO beam combinations for multiple MIMO spatial streams based on the results of the TX sector sweeping and the RX sector sweeping. No additional beam combination training is necessary in the second embodiment. If there are two MIMO spatial streams, then the two best MIMO beam combinations are determined. For spatial multiplexing, the best MIMO beam combinations are determined based on the highest SNIR. For spatial combining, the best MIMO beam combinations are determined based on the highest total combined power (SUM power). In step **515**, responder **502** feedbacks the best MIMO beam combinations to initiator **501**. Finally, in step **516**, initiator **501** and responder **502** perform beam combination refining, which fine-tunes the antenna beams for improved pointing accuracy and higher signal quality. More

details of the second MIMO training embodiment are now described below accompanied with FIGS. **6**A-**6**B.

FIG. **6**A illustrates a first step of the second embodiment of antenna beam training. The first step involves TX sector sweeping after initializing a MIMO training between an initiator and a responder. In the example of FIG. **6**A, which is similar to FIG. **4**A of the first embodiment, the initiator transmits training packets through total thirty-two (32) TX sectors—sectors **1** to **32**. The responder receives the training packets with an omni-direction beam. The responder then selects four TX sectors with the best signal quality (e.g., TX sectors **1**, **9**, **25**, and **28**). The responder also sends the selected TX sectors back to the initiator.

FIG. **6**B illustrates a second step and a third step of the second embodiment of antenna beam training. The second step involves RX sector sweeping. In the example of FIG. **6**B, the initiator transmits training packets using each of the selected TX sector (**1**, **9**, **25**, and **28**) to the responder, while the responder receives the training packets sweeping through total sixteen (16) RX sectors—sectors **1** to **16**. The responder then selects one RX sector with the highest signal quality for each of the selected TX sector (e.g., RX sectors **3**, **6**, **8**, and **15** for TX sectors **1**, **9**, **25**, and **28** respectively).

The third step involves the final selection of the best MIMO beam combinations. The already selected four TX-RX sector pairs are based on signal quality. In order to find the best beam combinations for multiple spatial streams, the selection criteria needs to include the mutual interference or leakage between the spatial streams. After considering the mutual interference or leakage, the best two beam combinations are finally determined. For example, TX**1**-RX**3** sector pair is selected for a first spatial stream SS#**1**, and TX**28**-RX**6** sector pair is selected for a second spatial stream SS#**2**. In this case, the received signal power from TX**1** to RX**6** becomes the interference to the TX**28**-RX**6** pair, and the received signal power from TX**28** to RX**3** becomes the interference to the TX**1**-RX**3** pair. Based on both the SNR and SNIR information, the TX**1**-RX**3** and TX**28**-RX**6** beam combinations are the best beam combinations for MIMO SS#**1** and SS#**2**.

Note that the second embodiment overall requires more training packets as compared to the first embodiment. From implementation perspective, the difference between the first embodiment and the second embodiment is whether the transmitting device needs to send training packets using omni-direction antenna pattern. The second embodiment does not require the implementation of semi-omni transmit antenna. In general, receiver omni-pattern is easier to form since one single antenna element would provide near omni pattern. The receiver omni-antenna gain is lower than the array antenna gain by the array gain. For transmitter, however, it is difficult to provide an omni-pattern. If a single antenna is used for generating omni-directional pattern, not only the antenna gain is reduced by the array gain but also the power gain is reduced proportional to how many power amplifiers are not used. As a result, the effective isotropic radiated power (EIRP) is reduced by array gain plus power gain.

FIG. **7** is a flow chart of a first embodiment of a method of antenna beam training for MIMO operation in accordance with a novel aspect. In step **701**, an initiator communicates with a responder a MIMO beam-training message to start a MIMO training procedure in a wireless network. The initiator is the transmitter of MIMO signal and the responder is the receiver of MIMO signal. Alternatively, the receiver of MIMO signal may also initiate the MIMO training procedure. In step **702**, TX sector sweeping is started. The initiator sends training packets through all TX sectors, and the responder receives the training packets with omni-direction beam. In step **703**, the responder sends a set of selected TX sectors with good received signal quality back to the initiator. In step **704**, RX sector sweeping is started. The initiator sends training packets with omni-direction beam, and the responder receives the training packets through all RX sectors. The responder then determines a set of selected RX sectors with good received signal quality. In step **705**, beam combination training is started. The initiator and the responder sweep through the selected TX sectors and RX sectors together. The responder records the received signal quality. In step **706**, the responder determines the best MIMO beam combinations for multiple MIMO spatial streams based on signal quality and based on interference or leakage among the different spatial streams. In step **707**, beam refinement is performed to fine-tune the antenna beams for improved signal quality.

FIG. **8** is a flow chart of a second embodiment of a method of antenna beam training for MIMO operation in accordance with a novel aspect. In step **801**, an initiator communicates with a responder a MIMO beam-training message to start a MIMO training procedure in a wireless network. The initiator is the transmitter of MIMO signal and the responder is the receiver of MIMO signal. Alternatively, the receiver of MIMO signal may also initiate the MIMO training procedure. In step **802**, TX sector sweeping is started. The initiator sends training packets through all TX sectors, and the responder receives the training packets with omni-direction beam. In step **803**, the responder sends a set of selected TX sectors with good received signal quality back to the initiator. In step **804**, RX sector sweeping is started. The initiator sends training packets using one of the selected TX sectors, and the responder receives the training packets through all RX sectors. The initiator repeats the process for each selected TX sector. The responder then determines a set of selected RX sectors with good received signal quality for each selected TX sector. In step **805**, the responder determines the best MIMO beam combinations for multiple MIMO spatial streams based on signal quality and based on interference or leakage among the different spatial streams. In step **806**, beam refinement is performed to fine-tune the antenna beams for improved signal quality.

Although the present invention has been described in connection with certain specific embodiments for instructional purposes, the present invention is not limited thereto. Accordingly, various modifications, adaptations, and combinations of various features of the described embodiments can be practiced without departing from the scope of the invention as set forth in the claims.

What is claimed is:

1. A method comprising:

communicating a beam-training message that initiates a multiple input and multiple output (MIMO) training procedure in a wireless network;

transmitting training packets using all TX sectors during TX sector sweeping and in response obtaining a set of selected TX sectors, wherein each of the TX sectors corresponds to a specific TX antenna beam;

transmitting training packets using omni-direction antenna pattern during RX sector sweeping and in response obtaining a set of selected RX sectors, wherein each of the RX sectors corresponds to a specific RX antenna beam;

starting MIMO beam combination training based on the selected TX and RX sectors by transmitting training packets using the selected TX sectors, wherein each MIMO beam combination includes one of the selected TX sectors and one of the selected RX sectors; and

obtaining one or more best MIMO beam combinations for multiple MIMO spatial streams, wherein each of the best MIMO beam combinations is selected based on the results of the MIMO beam combination training.

2. The method of claim **1**, wherein the beam-training message comprises parameters including a number of TX sectors, a number of RX sectors, a number of MIMO spatial streams, and a number of beam combinations.

3. The method of claim **1**, wherein the selected TX and RX sectors are determined based on signal to noise ratios (SNRs).

4. The method of claim **1**, wherein the best MIMO beam combinations are determined based on signal to noise plus interference ratios (SNIRs).

5. The method of claim **1**, wherein the beam combination training involves sweeping the selected TX sectors and the selected RX sectors together.

6. A method comprising:

communicating a beam-training message that initiates a multiple input and multiple output (MIMO) training procedure in a wireless network;

receiving training packets using omni-direction antenna pattern during TX sector sweeping and in response determine a set of selected TX sectors, wherein each of the TX sectors corresponds to a specific TX antenna beam;

receiving training packets using all RX sectors during RX sector sweeping and in response determine a set of selected RX sectors, wherein each of the RX sectors corresponds to a specific RX antenna beam;

starting MIMO beam combination training based on the selected TX and RX sectors by receiving training packets from the selected TX sectors using the selected RX sectors, wherein each of the MIMO beam combinations includes one of the selected TX sectors and one of the selected RX sectors; and

determining one or more best MIMO beam combinations for multiple MIMO spatial streams based on the results of the MIMO beam combination training.

7. The method of claim **6**, wherein the beam-training message comprises parameters including a number of TX sectors, a number of RX sectors, a number of MIMO spatial streams, and a number of beam combinations.

8. The method of claim **6**, wherein the selected TX and RX sectors are determined based on signal to noise ratios (SNRs).

9. The method of claim **6**, wherein the best MIMO beam combinations are determined based on signal to noise plus interference ratios (SNIRs).

10. The method of claim **6**, wherein the training packets during the RX sector sweeping are transmitted with an omni-direction antenna pattern.

11. A method comprising:

communicating a beam-training message that initiates a multiple input and multiple output (MIMO) training procedure in a wireless network;

transmitting training packets using all TX sectors during TX sector sweeping and in response obtaining a set of selected TX sectors, wherein each of the TX sectors corresponds to a specific TX antenna beam;

transmitting training packets using the selected TX sectors during RX sector sweeping and in response obtaining a set of selected RX sectors corresponding to each of the selected TX sectors, wherein each of the RX sectors corresponds to a specific RX antenna beam; and

obtaining one or more best MIMO beam combinations for multiple MIMO spatial streams, wherein each of the MIMO beam combinations includes one of the selected TX sectors and one of the selected RX sectors, wherein the selected TX and RX sectors are determined based on signal to noise ratios (SNRs) and the selected MIMO beam combinations are determined based on signal to noise plus interference ratios (SNIRs).

12. The method of claim **11**, wherein the beam-training message comprises parameters including a number of TX sectors, a number of RX sectors, a number of MIMO spatial streams, and a number of beam combinations.

13. The method of claim **11**, wherein the training packets during the RX sector sweeping are repeated for a number of total RX sectors for each of the selected TX sectors.

14. A method comprising:

communicating a beam-training message that initiates a multiple input and multiple output (MIMO) training procedure in a wireless network;

receiving training packets using omni-direction antenna pattern during TX sector sweeping and in response determine a set of selected TX sectors, wherein each of the TX sectors corresponds to a specific TX antenna beam;

receiving training packets using all RX sectors during RX sector sweeping and in response determining a set of selected RX sectors corresponding to each of the selected TX sectors, wherein each of the RX sectors corresponds to a specific RX antenna beam; and

determining one or more best MIMO beam combinations from the selected TX and RX sectors for multiple MIMO spatial streams, wherein each of the MIMO beam combinations includes one of the selected TX sectors and one of the selected RX sectors, wherein the selected TX and RX sectors are determined based on signal to noise ratios (SNRs) and the selected MIMO beam combinations are determined based on signal to noise plus interference ratios (SNIRs).

15. The method of claim **14**, wherein the beam-training message comprises parameters including a number of TX sectors, a number of RX sectors, a number of MIMO spatial streams, and a number of beam combinations.

16. The method of claim **14**, wherein the training packets during the RX sector sweeping are transmitted using each of the selected TX sectors.

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